an important part, during certain seasons, of all meteorological reporting services.

Some original and important experimental work along this line has been carried on by Lieut. W. F. Reed, U. S. N., aerological officer of the naval air station, Pensacola, Fla.[1] Lieut. Reed has been successful by the use of a radio receiver and direction finder to forecast the approach and movement of electrical disturbances over that particular portion of the Gulf covered by aviation operations from the Pensacola base. He has been able to detect the approach of these storms long before any local signs give warning of their approach and has been able to plot the movement of these storms, the directions from and to which they are moving, as well as their intensity. By this means he has been able to make the aviation operations from this base safer and much more successful. During the coming hurricane season it is to be hoped that this station, as well as others, may be able to carry on some extremely valuable experimental work, which in time may lead to the use of radio as a valuable aid to the hurricane-reporting service in the Gulf and Caribbean.

The field is large and there is need for considerable experimental work on the part of meteorologists acquainted and in touch with radio work. Our present forecasts of probability of the formation and approach of electrical disturbances and rather indefinite notice of their movements should in time be superseded by forecasts of a more definite nature, telling when to expect the disturbances at certain points, the direction and rate of movement, and their intensity. This type of service is at present rendered on a large scale in so far as the West Indian hurricanes are concerned, but in the case of nearly every one of these storms the position of their centers and the direction and rate of their movement is unknown for many hours, and in many cases days, by the forecasters who are charged with the task of reporting them, due to a lack of reporting stations over great areas of the Gulf and Caribbean during the progress of the storm. On the first notice of their formation and approach most vessels strike for port. Radio equipment, in addition to the broadened program of aerological observation, tide reports, and perhaps even vessel patrols now planned by the Weather Bureau, may in time fill this gap.

[1] Further details of Lieut. Reed's work will appear in a later issue of the REVIEW.

AEROLOGICAL OBSERVATIONS IN THE WEST INDIES.

It is generally thought that tropical cyclones (hurricanes) move approximately in the direction and with the speed of the air in the strata at no great height above the surface. If this be true, it is very desirable to obtain observations of free-air wind conditions on all sides of hurricanes, particularly on the north and west sides. Although working under severe restrictions of funds and personnel, the Weather Bureau is undertaking a campaign of this sort for the hurricane season of 1920, July to November, inclusive. Stations are being equipped and will be operated at San Juan, P. R., and Key West, Fla., in addition to those in the Gulf States at which observations are now being made by the Weather Bureau at Groesbeck, Tex., and Leesburg, Ga.; by the Meteorological Section of the Signal Corps at Ellington Field and Kelly Field, Tex.; and by the Naval Aerological Section at Pensacola, Fla. Moreover, two new stations are being organized by the Navy at Colon and Santo Domingo. These nine stations form a network which, it is believed, will furnish information of great value in the study of these destructive storms and in forecasting their direction and rate of movement. Moreover, the observations will be taken regularly twice each day, irrespective of the occurrence of hurricanes, and will, therefore, give us data as to trades, antitrades, etc., of the utmost interest from a theoretical point of view and of inestimable benefit in their practical application. It is probable that some of the stations will be continued throughout the year and that many others will be added, if funds permit, during the next two or three years.—*W. R. Gregg.*

THE MEASUREMENT OF TEMPERATURE, WITH SOME REMARKS ON OTHER PHYSICAL MEASUREMENTS, AND APPLICATIONS TO METEOROLOGY.[a]

By EDGAR W. WOOLARD.

INTRODUCTION—UNITS IN GENERAL.

Lord Kelvin once wrote, "When you can measure what you are speaking about and express it in numbers, you know something about it, and when you can not measure it, when you can not express it in numbers, your knowledge is of a meager and unsatisfactory kind. It may be the beginning of knowledge, but you have scarcely in your thought advanced to the stage of a science."

The general Theory of Measurements is familiar to everyone: There are five *fundamentally* different entities which physics is at present considering, viz, those the *concepts* of which are symbolized by the words *space, time, matter, electricity*, and *entropy.*[1] Hence, as was pointed out by Rucker,[2] we need five *fundamental units* for the measurement of physical quantities; those usually chosen are the units of length, mass, time, permeability, and temperature, although better selections probably could be, and have been, made.[3] However, it has been found that by arbitrarily fixing the magnitudes of the units corresponding to the three indefinables of mechanics—space, time, and matter—we are then enabled, through the Theory of Dimensions, to derive units for all other quantities. In a few cases, such as when dealing with heat and electricity, additional units which are sometimes called *secondary* fundamental units appear, but probably it is only our ignorance of the true nature of the quantities involved which prevents us from expressing these, too, in terms of the three primary fundamental units.[4]

The practical application of the above theory consists of the selection of the fundamental units, the construction of standards, and the devising of measuring instruments which may be calibrated by comparison with the standards.

[a] Delivered in part before Am. Metl. Soc., Apr. 22, 1920.

[1] These five concepts, together with that of *number*, are necessary and sufficient for the complete description of the universe so far as it is at present known to us from observation: the objective universe, however, is itself composed of only matter and energy—the other indefinables are not "things," strictly speaking, but only creations of the mind, *conventional frames imposed on the universe* for convenience in study and interpretation. *Cf.* H. Poincare: Foundations of Science; and K. Pearson: Grammar of Science.

[2] A. W. Rucker: On the suppressed dimensions of physical quantities. Phil. Mag., (5), 27, 104–114, 1889.

[3] See, *e. g.*, R. C. Tolman: The measurable quantities of physics. *Phys. Rev.*, (2), 9, 237–253, 1917.

[4] W. Watson: Textbook of Physics, new ed. London, 1911, pp. 5, 334; Rucker, *op. cit.*

The selection of the fundamental units, the fixing of their sizes, and, indeed, the whole system of units, are perfectly arbitrary; hence it has come about that even to-day there are in well-established use several different systems, each possessing its own advantages and disadvantages. The intrinsic value and significance of a quantitative result, however, lies not in the symbolical expression of that result; for once a concept has been formed there is a tendency to regard the resulting quantities as identical with the symbols which represent them, abstract science being thus cut entirely adrift from the fundamental notions related to the experience in which it had its origin, and being reduced to a species of mechanical game played in accordance with a set of rules which when divorced from their origin have the appearance of being perfectly arbitrary; if this view is adhered to for purposes of convenience, it is necessary at the end of any process to reconnect the symbols employed with the ideas which originally suggested them, and thus interpret the results of the purely symbolical processes.[5] It is of the highest importance to state upon what particular basis a set of symbolical expressions rests, so that in the comparison of observations separated in space or time it may be determined what part of the differences are significant and what part are due merely to differences in the manner of expression. The problem of equivalents and conversions in the theory of measurements furnishes an excellent illustration of this principle, as we shall see.

It may be proper to mention, first, some questions of general metrology which are not, perhaps, always sufficiently emphasized. The yard and the meter, the two units of length which are in common use at present, are each *defined* as the *length of the respective standard*. Now the yard is an arbitrary length, the outgrowth of the rather confused and indefinite measures of early England; its length was definitely fixed by the construction of the original imperial standard yard by Bird in 1758; this original standard was destroyed in 1834 in the fire of the Houses of Parliament, and a new one was constructed and compared with the copies of the original which had been sent to various countries; while the differences in length which were found were unimportant, still there were differences; it must be remembered that because of the inherent limitations of man it is impossible to *exactly* duplicate a length, or *exactly* measure one; it is perfectly evident that there is only *one* accurate yardstick in existence, viz, the defining standard,[6] and all measurements must take account of not only the error of the instrument used, but also of the error of the standard and the error of the standardization. Such refined considerations, while perhaps not of much importance so far as individual observations are concerned, become of vital importance when observations are to be compared, for then all the measurements must be reduced to a common basis, and this can not be done until it is known to what basis each was reduced by the original observer. The meter is also an arbitrary length, although originally intended to be one ten-millionth of the earth's quadrant; it is not in any way superior to the yard except in the advantages conferred by the decimal character of the metric subdivisions. The meter is the length of the international meter, kept near Paris, which is a *copy* of the *original defining standard*.

The coexistence of more than one system of units necessitates the frequent use of the equivalent of a unit in one system in terms of the corresponding unit in another system; the yard and the meter, however, are incommensurable lengths to start with, and the always-present error of observation would prevent either one from being exactly measured in terms of the other, anyway, even though the defining standards themselves be used in the comparison; measurements performed at different times by different observers always give slightly different equivalents, some one of which must be arbitrarily adopted, usually by means of legislation on the subject.

In the United States of America, the unit of length is fixed by law to be the meter, which is defined to be the length of the international meter, a copy of which is kept by the Bureau of Standards; the yard is *defined* by law to be $\frac{3600}{3937}$ meter. In Great Britain, on the other hand, the unit of length is fixed by law to be the imperial yard, and the *meter* is defined by law to be 1.093614 yards. None of these equivalents is exactly that given by the best comparisons of the standards; the fact that the American and the British yard and meter are, therefore, probably slightly different from each other, and that the equivalents differ from each other and from the actual equivalents, shows the care needed when stating the results of measures of length. Somewhat similar remarks apply to measurements of other physical quantities.[7]

Clearly, in scientific work we should, whenever it is necessary to employ equivalents, use the true values as nearly as they can be determined, and not the arbitrary legal approximations. Whenever it is necessary to make use of tables of any kind, it must be carefully noted upon what basis they have been constructed. Meteorology furnishes a good illustration of the preceding principles.

So far as meteorology is concerned, the basis of numerical computations was set out authoritatively in the International Tables of 1890:[8]

> It has been the object of the meteorological authorities in all countries that the numerical values given in this publication should form the basis of all tables of conversion and computation which are employed by observers and students throughout the world, so that the meaning of any small differences in results should be freed from ambiguity on account of the process of computation.
>
> Meteorological questions nearly always depend for their solution on the comparison of results from different parts of the world, and comparability is often more important than extreme numerical precision, so that the values used in the computation of the International Tables are sufficiently accurate for all the computations of meteorogical practice and will remain so for many years to come, but in the meantime alterations in the accepted comparisons of fundamental standards of the various countries may receive, and some have received, the sanction of law, and it is hardly permissible to an official to display, or affect to use, tables which are ostensibly based on equivalents which are not lawful.
>
> The suggestion is sometimes lightly made that a new edition of the tables is required to bring them up to date, but the recomputation of tables is a work of great labor without any justification in the results to be achieved.
>
> Still, the progress in metrological exactitude which naturally follows the establishment of such institutions as the Bureau International des Poids et Mesures, the Reichsanstalt, the National Physical Laboratory, and the Bureau of Standards, must not be disregarded; and the horizon of meteorological computation has been much extended by the development of the study of the upper air which requires the tables for computation to be similarly extended over ranges which were outside the meteorological practice of 1890.[9]

The International Tables are based on the values of the equivalents which were then most widely accepted;

[5] *Cf.* E. W. Hobson: Theory of Functions of a Real Variable and the Theory of Fourier's Series. Cambridge Press, 1907, pp. 9, 10.

[6] It is not certainly known that the standards are not subject to secular change.

[7] See L. A. Fischer. History of the Standard Weights and Measures of the United States. U. S. Bur. Stand. *Sci. Paper 17*, 1905, especially pp. 379-381; also Centennial Celebration of the U. S. Coast and Geodetic Survey, Washington, 1916, pp. 25-39 (S. W. Stratton, The Bureau of Standards and its Relation to the U. S. Coast and Geodetic Survey).

[8] Tables Météorologiques Internationales publiées conformément à une decision du Congres tenu à Rome en 1879. Paris, 1890.

[9] British Meteorological Office, Computer's Handbook, Introduction, pp. 4-5, 1916.

the fourth edition of the Smithsonian Meteorological Tables[10] is based on the United States statutory equivalents, and on new values for standard gravity, density of mercury, etc., all of which must be considered when comparing older data and tables with modern ones.[11]

It is unnecessary to set forth here that which has been so often set forth, and which is almost self-evident, viz, the extreme desirability of *uniformity* in the matter of systems of units—*world-wide* uniformity, not only among scientists, but between scientists and laymen; only under such a condition—one which seems impossible to bring about—is it possible to have the fullest cooperation, appreciation, and understanding, and the most rapid advance in scientific knowledge.

Meteorology, being essentially the physics of the air, will employ the same system of units as physics employs, with such special adaptations and extensions as may be necessary. Until recently, however, there has been an estrangement between meteorology and the other physical sciences as regards the system to be employed; the same estrangement that still exists between scientific education and practical life. "If science is to be a part of practical life, the units of science and the units of practical life must be the same. One thing or the other: Either practical folk must learn to use metric units, or * * * men of science must use British units in their laboratory courses. The present divorce between education and practice is ruinous for both."[12] The intimate relations between meteorological work and the practical affairs of the general public for which the work is largely intended, has resulted in the use of the British units. At present "if in a country assembly for the advancement of science, an unknown stranger should get up and speak in metric units, the initiated physicist would at once say 'he must be one of *us*,' and the uninitiated meteorologist would say 'he is one of *them*.'"[13]

Furthermore, the difficulties of metrology are great enough without adding to them in any case by the adoption of a system of units which are not absolute, i. e., a system of units which depend for their values upon location in time or space; furthermore, if absolute units are the best for theory, as they undoubtedly are,[14] then they are the units of the future, for the practical applications of meteorology must ultimately be guided by theory just as those of astronomy are at the present day.[15] A vast number of considerations leave no doubt but that absolute units are also best for the use of instructors and lecturers who wish to interest students of physics and mathematics in meteorology, and for the presentation of the results of meteorological observations and studies to the public.[16] Various factors have contributed during the past several years to an increased use of the C. G. S. system in meteorology, even in the presentation of the daily reports to the public. Unfortunately this movement has come at a time when international agreement and standardization was impossible; we may look forward to such international action in the near future—some points have already been considered by the International Meteorological Conference.[17] Meanwhile some of the decisions of the international conferences on weights and measures in general are of special interest to meteorological circles.[18]

It has been said that meteorology stands in the way of the general adoption of metric units; this can no longer be maintained, however;[19] on May 1, 1914, the British Meteorological Office adopted metric units on its daily maps and reports and absolute units in its barometric work (recently F. temperatures were restored; absolute and metric units are now widely used in the official publications of the meteorological services in a number of countries, particularly in aerological work, although the transformation is still very far from being complete, especially in the United States.[20] Even in the present system of *metric* meteorological units, there is much that is unsatisfactory. "In referring to units of measurement it is customary to speak about the metric 'system' in contradistinction to the English want of system; but in meteorology the metric measures are not more systematic than the British, for both are arbitrary."[21]

In adopting the metric system meteorologists aspired to do what physicists had often aspired to do, but had never had the courage or coherence to carry out, viz, use pressure units for pressure measurements, reserve length units for length measurements, and change the thermometer scale so as to abolish negative temperatures, which are a survival of the time anterior to a knowledge of the conservation of energy, and have sooner or later to be explained away with much labor and practical inconvenience.[22] To what difficulties this has led, particularly as regards the absolute unit of pressure, is well known.[23]

Some of the difficulties, particularly in the case of meteorology, arise from the fact that the fundamental or "normal" system of units, such as the C. G. S., can not be equally convenient for practical use in all fields of science. The practical systems, derived from the C. G. S. system, have been formally defined by international action only in the case of electrotechnology;[24] the electrical engineers did something akin to what the meteorologists did when the latter made the unit of pressure 10^5 C. G. S. units.

The question of thermometer scales, mentioned above incidentally, raises difficulties all its own; very hazy ideas of temperature and its measurement prevail in the minds

[10] Smithsonian Meteorological Tables, Fourth Revised edition, Washington, 1918.
[11] See the *Introductions* to the International Tables and to the Smithsonian Tables.
[12] Sir Napier Shaw: Units and Unity, *Nature*, 101, 326–328, 1918.
[13] W. N. Shaw: Pressure in absolute units. MONTHLY WEATHER REVIEW, 42: 5–7, 1914
[14] V. Bjerknes: The C. G. S. System and Meteorology. MONTHLY WEATHER REVIEW, 42: 143–144, 1914.
[15] Sir Napier Shaw: The Outlook of Meteorological Science. MONTHLY WEATHER REVIEW, 48: 34–35, 1920; Shaw: MONTHLY WEATHER REVIEW, 42: 5, 1914.
[16] See Shaw, MONTHLY WEATHER REVIEW, 42: 5–7, 1914; British Meteorological Office, Computer's Handbook, Introduction; and The Observer's Handbook, 1919 ed., pp. viii–xx; also, The Seaman's Handbook of Meteorology, 3d ed., 1918, pp. vii–xviii.
[17] MONTHLY WEATHER REVIEW, 47: 852, 1919.
[18] E. g., as to the value of gravity to be employed in the reduction of the barometer, see *Nature*, 104, 13, 1919.
[19] Shaw: *Nature*, 101, 326–328, 1918.
[20] An excellent discussion of the difficulties of and the reasons for the adoption of the metric system in meteorology, the status of the system in the meteorological services of the several countries, and a complete systematic presentation of C. G. S. meteorological units are given in the British Metl. Office, Observer's Handbook, 1919 ed., pp. viii–xxvi; see also the Computer's Handbook, Introduction, pp. 5–14, 1916. The status of the metric system in general, in all countries, is set forth in the publications of the Bur. Int. des Poids et Mesures—see, e. g., Travaux et Memoires, t. xvi, Paris, 1917 (*Nature*, 104, 12–14, 1919; Science Abstracts, A, 22, 410, 1919), and Rev. Gen. d'El., 6, 311–312, 1919.
[21] On the adoption of the metric system in meteorology, consult: A. McAdie, New Units in Aerology, *Nature*, 93, 58, 1914; Shaw, *Nature*, 101, 326–328, 1918; New Daily Weather Map, MONTHLY WEATHER REVIEW, 42: 35, 1914; Metric System for Aeronautics, MONTHLY WEATHER REVIEW, 44: 627, 1916; A. McAdie, Suggested Reform in Meteorological Methods, MONTHLY WEATHER REVIEW, 36: 372–374, 1908; R. Inwards, Metric System in Meteorology, *Quar. Jour. Roy. Metl. Soc.*, 33: 165–171, 1907.
[22] Shaw: MONTHLY WEATHER REVIEW, 42:5, 1914.
[23] Consult: C. F. Marvin, Nomenclature of the unit of absolute pressure, MONTHLY WEATHER REVIEW, 46:73–75, 1918; G. Platania, Le Unita Assolute in Meteorologia, *Rivista Marittima*, Oct., 1918; Standard units in aerology, MONTHLY WEATHER REVIEW, 42:141–143, 1914; F. J. W. Whipple, Absolute scales of pressure and temperature, *Proc. Phys. Soc. Lond.*, 31:237–241, 1919, and *Chem. News*, 119, 189–191, 1919; Proposal to express all measurements of atmospheric pressure by a universal measurement of force, *Quar. Jour. Roy. Metl. Soc.*, 35:132–134, 1909; Terminology in dynamic meteorology, *ibid.*, 40:160–163, 1914; E. Gold, Barometer readings in absolute units and their correction and reduction, *ibid.*, 185–201, 1914; C. F. Marvin, Nomenclature of the unit of absolute pressure, *ibid.*, 44:225–230, 1918; F. J. W. Whipple, Dynamical units for meteorology, *Nature*, 93:427–428, 1914; R. A. Sampson, Meteorological unit of pressure, *Nature*, 101, 353, 1918; A. McAdie, Standard units in aerology, *Science* (N. S.), 39:391–392, 1914; A. McAdie, Unit of pressure, *ibid.*, 45:385, 1917; Guillaume, Progres du Systeme metrique, 1913, pp. 43, 79; Phys. Soc. of France, Recueil de constants physiques, 1913, p. 6; Brit. Assoc. Adv. Sci., *Rept.* 1873, pp. 222–225; *Jour. Amer. Chem. Soc.*, 26:408, 1904; 36:491, 1913; *Phys. Rev.*, 5:212–229, 1915; Smith. Phys. Tables, 1916, p. 346; MONTHLY WEATHER REVIEW, 44:191, note 4, 1916. In conformity with the system of naming units after great scientists, the names "pascal" and "abbe" have been proposed instead of "bar." The U. S. Army shows a strong inclination to completely abandon even the partial use of the meteorological and other metric measures which it initiated during the recent war.
[24] See U. S. Bur. Stand. *Sci. Paper 292* and *Circular 60*, on the International electrical and magnetic units; and Proces-Verbaux, Comite Int. des Poids et Mes., 1911, p. 209, Comptes Rendus, Conference Generale des Poids et Mes., 1913, pp. 14, 51–60.

of most people, including many professional physicists; confusion and inaccuracies are present in many textbooks. Therefore it seems quite appropriate to give the whole subject of thermometry a special and complete exposition—one which is applicable to precise physical laboratory measurements as well as to meteorological observations.

THERMOMETRY.

The molecular and kinetic theories of matter, although 25 centuries old, have only recently, through the demonstration of their soundness,[25] been raised above the position of mere convenient working hypotheses. Until the establishment of these theories thermometry, although nearly as ancient as they, was only a rough empirical subject with no theoretical foundations; hence, present-day precision thermometry, at least on the theoretical side, is essentially a modern development. In an exposition of the principles of thermal measurements, it may therefore be assumed as an already established fact that heat is a form of *energy*, and one which stands in a very special relation to matter—viz, it is that part of the total internal energy of matter which is due to the motions of the molecules relative to one another. The determination of the absolute amount of heat contained in a given mass is the measurement of the sum total of the kinetic energy of the molecules with reference to each other; if the molecules could be brought to rest among themselves the mass would then possess no heat. Since heat is a form of energy, a quantity of it may be dynamically measured by determining the number of units of work to which the heat is equivalent.

To prevent possible confusion in the mind of the reader, it may be stated here that radiant energy is not heat, although it is converted into heat upon being absorbed by any object in its path; and, conversely, heat has a great deal to do with the production of radiation. The transference of energy by radiation and absorption constitutes the most important agency in the diffusion of heat.

The term "heat" is employed in ordinary language with a number of slightly different meanings. The sense of touch first gives rise to the concept of heat, and from this there arises the further popular conceptions based on the different sensations produced by bodies when termed hot, warm, or cold, which imply a crude conception of a continuous scale, the place of any body in this scale being denoted by its *temperature*, so-called; the hotter body is said to have the higher temperature.

From the nature of heat, it is self-evident that a large and a small body, each composed of the same substance, may possess equal *degrees* of molecular motion, and hence give rise to identical physiological sensations, and yet contain vastly different total *amounts* of molecular motion, i. e., of heat, according to their respective masses or total numbers of molecules. Thus the temperature of a body is, qualitatively speaking, its degree of hotness, in contradistinction to the actual quantity of heat present in the whole body.

In scientific work it is, of course, necessary to have a more definite and reliable indication than is afforded by the sense of touch; measurements of heat have necessarily been based on some *measurable physical effect* of heat, rather than on any difference of physiological sensations, the scale of measurement being so chosen as to give hotter bodies higher temperatures in agreement with our ordinary ideas of differences of hotness or coldness so far as the two can be compared.

[25] *Cf.* R. A. Millikan: The Electron, pp. 6-10, 1917.

The phenomenon which has been most generally employed for the above purpose is that of the volumetric expansion of bodies with increase of heat content. This effect of heat was known in very ancient times. *The expansion, while not varying exactly in a simple proportion to successive increments of heat, still approaches closely to a linear relation.* Expansions or contractions, then, of a body, relative to any initial volume arbitrarily selected as a starting point, measure *relative* increments or decrements of heat, *equal changes in heat content corresponding to nearly equal changes in volume.*

In the writings of Philo of Byzantium (third century B. C.) and of Hero of Alexander (first(?) century B. C.) we find the earliest application of these principles of which we know—viz, descriptions of an apparatus which represents the primitive idea of a thermoscope.[26] A translation of Hero's book was studied by Galileo, Porta, and Drebbel, and gave, about the year 1600, to all three men the idea of constructing a thermoscope. Galileo revived the instrument in the form of a glass globe opening into a narrow tube, and partly filled with water, the whole being inverted and dipped into a vessel of water; the height at which the water stood in the tube as the air in the globe expanded and contracted indicated the relative thermal condition of this air; since the relatively small amount of matter composing the instrument permits it to come quickly into thermal equilibrium with the surroundings, it is easy to see how the indications of a thermoscope are also qualitative indications of the thermal condition of the immediate environment; for quantitative relationships to be established, the conditions at equilibrium must be supplied by theory.

Galileo's thermometer was extensively introduced by Sanctorius of Padua; within a few years the instrument had been inverted, and otherwise improved by Galileo and his pupils, and by 1641 the modern type of thermometer was in use—a bulb filled with spirit of wine or other liquid, the tube being sealed, and graduated in accord with some standard system. In such an instrument, increment of heat (i. e., of amount of molecular motion) in the surrounding medium will, at equilibrium, cause the *same* increments of heat in the material of the thermometer bulb, *relative to the initial amount* (regardless of whatever quantitative relations may exist); the resulting proportional expansion of the thermometer fluid may therefore be used to measure the *relative* heat content of the environment, without any knowledge as to masses, specific heats, or coefficients of expansion[27]—provided always that the *thermometer fluid* has a constant coefficient of expansion which bears a linear relation to heat increments: This latter condition is not met with in the case of any actual substance, as we have noted, and consequently corrections must be determined and applied to eliminate the error thereby introduced.

We thus *define differences of temperature as proportional to differences of heat content*, the latter being measured by the expansion of the material in the thermometer bulb indicated by an arbitrarily graduated scale on the stem.

The unit of *absolute* quantity of heat is then *defined* as the amount of heat necessary to cause a certain specified increment in the heat content, i. e., a certain specified temperature change, of a certain mass of a certain substance, thus making the whole art of calorimetry depend upon that of thermometry:

[26] G. Hellmann: The dawn of meteorology. *Quar. Jour. Roy. Met. Soc.*, 34, 226-228, 1908.

[27] The loss of temperature by a hot body is, after equilibrium, not generally equal to the gain of temperature of a cold body in contact with it, but that of degree of molecular motion obviously is. Account must be taken, in practice, of the expansion of the bulb itself, too.

The temperature of a body is its thermal state considered with reference to its power of communicating heat to other bodies; the *continuous series of such thermal states* passed through by any one substance, as its heat content is continuously increased or decreased, *defines a temperature scale;* any arbitrary system of *uniquely designating* or labeling each temperature of the scale constitutes a *thermometer scale*—when some particular property of some particular substance, for example the volumetric expansion of mercury, or the resistance of a platinum wire, is selected to define a scale of temperatures it still remains necessary to select some arbitrary system, say of numbers, by which to label uniquely each successive thermal state which is indicated to us by means of the use of that property.

A thermometer constructed according to the above definitions will, then, indicate uniquely the temperatures and temperature changes of its environment, and hence, from the definition of temperature differences, also indicate differences of actual heat content, so that, arbitrarily defining the unit of absolute amount of heat as we have done above, it is clear that with the mechanical equivalent of this latter unit known our problem is completely solved. The total amount of heat in a body can then be calculated provided we know the mass, temperature, and the specific heat at all temperatures; and in any case *changes* in the heat energy can easily be experimentally determined, although we can not, in this paper, go into the details of calorimetry.

Obviously, working temperature scales and thermometer scales should be so chosen that results expressed in terms of them may be capable of ready translation into terms of molecular processes and conditions as indicated in the preceding paragraph, for temperature measurements are only a means to an end. Our sensations provide us with a simple and general criterion for deciding whether the temperatures of two different bodies are equal or unequal, and by a further convention we tell with certainty what is the sign of the difference in temperature between two bodies; diffusion of heat always takes place from hotter to cooler bodies. Now, our preceding discussion, as well as the mere fact that we speak of the body which cools off the more quickly as having the *higher* temperature far more often than we speak of it as having the *greater* temperature, betray the fact that we do not look upon temperature as a quantity measurable in the usual sense. When we go beyond the bare statement that the temperature of one body is equal to, lower (less) than, or higher (greater) than that of a second body and *assign numerical values* to temperatures by means of arbitrary graduations on the stem of a thermometer, we are, strictly speaking, not *measuring* temperatures, but *numbering* them; there *is* no such thing as *measuring* temperature in the sense in which the term "measure" is commonly used in physics, i. e., there is no such thing as direct comparison of two intervals of temperature which are not coincident at both ends. Temperature is not an extensive magnitude, i. e., it does not possess an additive nature such that a given quantity of it may be regarded as being the sum of a number of smaller quantities of the same kind; the "measurement" of such a quantity as temperature must be effected by some device in which the magnitude to be measured is put into a one-to-one relation with a series of quantities which *have* extensive magnitude. In other words, we adopt some method by which we may assign to each separate temperature a definite number, and there must be a one-to-one correspondence. The method must be unequivocal in assigning one, and only one, number to each temperature and in never giving the same number to two different temperatures. This is the one essential fundamental principle in constructing a scale of temperature. If we conform to it, we are free in other respects to choose our scale as we please, the choice being, in any case, arbitrary.[28]

For a century after Galileo's time great confusion prevailed; many different substances were used in the thermometer bulbs, and innumerable different systems of arbitrary graduation for the stems were employed. Out of the chaos there finally emerged three systems, because the founders of these systems manufactured instruments of such high quality and in such great numbers that they came to be recognized as standard.[29] The Fahrenheit thermometer originated at Danzig in 1714; mercury was used for the fluid, and the two known temperatures—the freezing and boiling points of water—which had previously been employed by Huyghens in 1665 were utilized to give the graduation. The centigrade scale was introduced by Celsius and Linnæus at the University of Upsala in Sweden, 1742, and the Reamur by the French physicist of that name, 1731, although both were later somewhat modified by others.

The main object to be secured in thermometry is that all thermometers shall be strictly comparable; the simplest means of obtaining this object is by comparing all thermometers, directly or indirectly, with some standard instrument; when thus properly corrected, all thermometers will be copies of the same original and will agree in their indications. Thermometers may then be constructed of other fluids than the one used in the standard, or by measuring some effect of heat other than that made use of in the standard; the condition implied in all cases being that the thermometers shall all be graduated so as to agree with the standard, and also that the particular property of matter made use of shall always give the same indication when the temperature is brought again and again to the same value.

Now, in spite of the fact that, as we have specifically stated, temperature differences are proportional to differences of heat content, it is far more convenient in practice to *define equal increments of temperature as those which give equal increments of, say, volume to the substance employed:* this, of course, does not agree with the previous definition, because all substances differ from each other in their physical properties, and all depart somewhat from an ideal behavior, so that although no matter what fluid be employed in a thermometer bulb it will, in accord with this second definition, indicate temperature increments quite satisfactorily, yet two thermometers employing different fluids will not ordinarily read exactly the same numerically (supposing the same system of graduation to be used for both) when exposed to identical thermal environments; and equal *intervals* on either one will correspond to irregularly variable increments of *heat. Each thermometer defines its own scale of temperatures:* and either we must arbitrarily adopt a standard by merely *conventionally agreeing* upon some one instrument and then working out the complicated series of corrections necessary for the translation of its indications into terms of molecular processes, or we must discover a temperature scale independent of these vagaries of matter for our standard. The selection of a standard temperature scale is, of course, independent of the selection of a thermometer scale, or system of labeling, to go with it. The position in the *temperature* scale of one or more easily

[28] Edgar Buckingham: Note on the Radiation Formulas and on the Principles of Thermometry, MONTHLY WEATHER REVIEW, 31: 179, 1903; J. Rice, *Scientific American Supplement,* May 3, 1919, p. 287.

[29] See Cajori, History of Physics, for a history of thermometers.

reproducible *standard temperatures* must be known, and the whole scale should conform to nature and be easily and accurately reproducible at any time; then the arbitrary thermometer scale may be agreed upon by selecting some point in the thermometer scale as a *zero point*, some continuous portion as a *fundamental interval*, and some fraction of the fundamental interval as a *unit*.

The mercury-in-glass thermometer was originally taken as the standard. It was stated, among other things, that mercury "expands uniformly," and yet no standard of reference was given by which this uniformity was supposed to have been established. In time, it was found that slightly different temperatures would be indicated by different instruments, depending upon the kind of glass employed; differences were found even in thermometers made from the same ingot of glass; in addition, mercury, as pointed out before, gives us an arbitrary scale of temperature differing, probably, from every other similar scale; air does not expand quite uniformly if mercury be the arbitrary standard, and vice versa. After the discovery of the gas laws, some monumental researches on the expansion of gases were carried out by Regnault, who, after studying the whole subject of thermometry very critically, introduced the use of the air thermometer as a standard, comparing its indications with those of a mercurial instrument; later investigators experimented with other gases similarly; but because of the differing properties of the various gases, none of which is perfect, the gas scales also are incapable of giving a solution of our problem.[30]

However, Lord Kelvin finally showed from theoretical considerations that Carnot's function supplies a means of measuring temperatures independently of the properties of any particular substance. *Carnot's Theorem* asserts that the efficiency of any perfect thermal engine working periodically and reversibly by taking in heat from a hot body and giving out heat to a cold body, is the same for all such engines and for all substances employed in them, being a function of only the temperatures of the hot and cold bodies. If E be the efficiency, and Q_1 and Q_2 the heat taken in and given out respectively, then [31]

$$E=\frac{Q_1-Q_2}{Q_1},$$

which may be put in the form

$$\frac{1}{1-E}=\frac{Q_1}{Q_2}.$$

Since, from the theorem,

$$E=f'(t_1, t_2),$$

we have

$$\frac{Q_1}{Q_2}=f(t_1, t_2).$$

If we assign to any two temperatures *numbers* such that

$$\frac{\theta_1}{\theta_2}=\frac{Q_1}{Q_2},$$

we have the thermodynamic scale introduced by Lord Kelvin in 1854. Then,

$$E=\frac{\theta_1-\theta_2}{\theta_1}.$$

[30] The initial pressure is a factor in the use of gas thermometers; the barometric pressure of course influenced the thermoscope of Galileo. The details of the construction and manipulation of the various instruments of thermometry must be sought elsewhere than in the present paper.

[31] For the complete explanation of the following derivations, see Preston, Theory of Heat, 2d ed., 1904, pp. 709-713.

It is easily shown that the scale of temperatures which would be defined by a perfect gas, employed with a thermometer scale with its graduations numbering from the point at which the gas contained no heat—no molecular motion—whatever, would satisfy the above condition.[32] A perfect gas is one which would obey Boyle's Law perfectly throughout all ranges of temperature.[33]

Since the coefficient of expansion of a gas is closely 1/273 on the centigrade scale, the extrapolated point on the scale of the constant-volume hydrogen thermometer at which the gas pressure would vanish—corresponding under the ideas of the kinetic theory to a complete absence of heat—is about −273° C., the so-called "absolute zero." The zero of the thermodynamic scale is identical with the absolute zero of a perfect gas, and since the absolute thermodynamic temperatures and absolute temperatures on the gas scales are both of frequent occurrence, it is desirable to employ a thermometer scale such that the numerical symbol of a temperature will be the same on both scales. The *thermodynamic scale of temperatures is the only one which is independent of the properties of some one particular substance*, and evidently is not realizable in practice; at the same time, from its relation to the gas laws, it is clear that on this scale, temperature differences *are* proportional to heat increments; in this case, *our two different definitions of temperature differences are equivalent*. Our considerations have brought us to two independent and discordant temperature scales, (1) the theoretical thermodynamic scale which can not be realized in any practical working thermometer, and (2) a practical instrument depending upon the volumetric expansion or other physical properties of substances we may find it convenient to employ, but the indications of which are somewhat difficult to translate into terms of molecular processes. If we can accurately determine the *deviations at all temperatures* of any one or all of these practical thermometers from the thermodynamic scale, then our problem will have been completely and accurately solved in spite of the difficulties introduced by the irregularities in the behavior of matter.

As a matter of fact, the scale defined by any one of the more permanent real gases is a very close approximation to the thermodynamic scale; furthermore, by conducting appropriate investigations upon the flow of actual gases through porus plugs, their deviations from the behavior of perfect gases can be ascertained.[33] Experiments show that in the case of hydrogen the deviations from the thermodynamic scale are so small except at very low and very high temperatures that a hydrogen gas thermometer may be taken for all practical purposes as a realization of the ideal scale.

The equation $\theta_1/\theta_2=Q_1/Q_2$ defines only the ratio of two temperatures and not their numerical values; when the further condition is imposed [34] that the temperatures of the melting point of ice and condensing point of steam shall differ by any arbitrary number of degrees, then the location of these points fixes the numerical value of every other temperature independently of the laws of expansion of any particular substance.

On October 15, 1887, the International Committee on Weights and Measures passed a resolution adopting as the standard thermometric scale for the international service of weights and measures the *centigrade scale of the hydrogen thermometer*, having the zero point of the *thermometer* scale at the *temperature* of melting ice; the

[32] Preston, op. cit., p. 716; Edgar Buckingham, On the definition of the ideal gas, U. S. Bur. Stand. *Bull.*, 6, 413, 1909.

[33] *Cf.* Buckingham, op. cit.

[34] Preston, op. cit., p.714-716.

fundamental interval the difference of temperature of melting ice and of the vapor of boiling distilled water, all under standard atmospheric pressure; the unit or *degree* $\frac{1}{100}$ of the fundamental interval; the hydrogen in the thermometer to be taken at an initial pressure of 1 meter of mercury—that is, $\frac{1000}{760}$ or 1.3158 times the standard atmospheric pressure. Now, if we thus specify that the numerical values of the temperatures of the freezing and boiling points shall differ by 100, and that the temperature of the freezing point shall be denoted by 0, than the *centigrade thermodynamic* temperature is the number of degrees from the ice point to the given temperature to be numbered; by "the correction of the gas scale to the thermodynamic scale" is meant the difference between the centigrade scale of the gas thermometer and the centigrade thermodynamic scale, the latter being now the standard scale; these corrections therefore vanish at 0 and 100.[35]

Owing to the great experimental difficulties involved in the use of precise gas thermometers of any form and the limitations in range of temperature they can cover, it is necessary to establish a practical working scale which should represent the thermodynamic scale as closely as possible in the light of existing knowledge and be definite and easily reproducible. Such a working scale may be defined by means of certain fiducial temperatures or fixed points, together with a specification of the method of interpolating between the fixed points. Then the practical working instruments which meet the needs of ordinary observational work and, in some cases, by safe extrapolations, extend the range to temperatures otherwise unattainable with the gas thermometer itself, may easily be standardized by comparison with this working scale.

The leading laboratories of the world have adopted the *platinum resistance thermometer* as the working or interpolation instrument in the interval −190° to 450°, the fixed points or fiducial temperatures being those defined by the following phenomena, where the values are those on the centigrade thermodynamic scale:[36]

Boiling point of oxygen	−183. 0
Sublimation point of carbon dioxide	− 78. 5
Freezing point of water	0. 0
Boiling point of water	100. 0
Boiling point of sulphur	444. 6

Thermoelectric junctions, composed of suitable combinations of metals, also serve for effecting temperature measurements, and in the interval 450° to 1,100° the platinum thermocouple—90 per cent platinum, 10 per cent rhodium—is used as the interpolation instrument, being calibrated at the freezing points of zinc (419.4°), antimony (630.0°), and copper (1,083.0°).

Finally, *optical pyrometers* must be resorted to in the measurement of extremely high temperatures. The ingenuity, art, and skill of the physicist are taxed to the utmost to adequately evaluate or number all the temperatures which come within his experience on the one ideal thermodynamic scale which justly constitutes the accepted standard.

The *mercury-in-glass thermometer*, carefully standardized by direct or indirect comparison with a standard gas thermometer, is a familiar example of an exceedingly convenient and widely used instrument for temperature measurements over a certain range.[37]

It will now be recalled, however, that the most desirable scale is not the centigrade thermodynamic, but the thermodynamic employed with a system of graduation starting at the absolute zero; it is evident that to reduce the reading of a standardized thermometer to this *absolute thermodynamic scale* we merely add to the reading, after the latter is corrected to the thermodynamic scale, the *thermodynamic temperature of the ice point*. After having specified that the fundamental interval shall be 100°, there are several methods of evaluating the ice point on the thermodynamic scale, but the problem is far from being simple, and there is still some uncertainty in the value; it is probably very close to 273.°13.[38] For practical purposes we may add 273 to the centigrade reading and call the resulting thermometer scale the "Approximate absolute."[39]

In English-speaking countries neither the absolute nor the centigrade thermometer scales are in common use outside the laboratory. As Sir Napier Shaw says, "Our practice of using one set of units in the laboratory and another set in practical life can only be described as stupid." The absolute thermodynamic scale has some reality about it—it conforms to physical phenomena and to the nature of things as we find them, instead of being based upon the predilections of men.[40]

In conclusion, I wish to acknowledge the helpful suggestions and interest of Prof. C. F. Marvin, Chief of Bureau, during the preparation of this paper.

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[35] Edgar Buckingham: On the establishment of the thermodynamic scale of temperature by means of the constant-pressure thermometer, U. S. Bur. Stand. *Sci. Paper 57*, 1907, pp 237-243, 274. The corrections are tabulated in Guillaume, Les Recents Progres du Systeme Metrique, p 48, in Travaux et Memoires du Bureau International des Poids et Mesures, t. XVI, 1917.

[36] Waidner, C. W., et al : The standard scale of temperature, *Jour. Wash. Acad. Sci.*, 10, 276–277, 1920: U. S. Bur. Stand., *Circ. 35*, Melting points of the chemical elements and other standard temperatures, 1919.

[37] The numerous publications of the U. S. Bureau of Standards may be consulted for the details of the theory, construction, and manipulation of the various classes of instruments mentioned above. On standardization, etc., see, e. g., U. S. Bur. Stand. *Circ.* 8, Testing of Thermomenters, 1911; *Sci. Paper* 69, On the standard scale of temperature in the interval 0° to 100° C., by C. W. Waidner and H. C. Dickinson, 1907.

[38] Buckingham, op. cit.; Preston, op. cit., pp. 714–717.

[39] C. F. Marvin: Shall we revise our nomenclature for thermometric scales? MONTHLY WEATHER REVIEW, 45; 534, 1917; *Nature, 101*, 14, 1918; Smithsonian Meteorological Tables, 4 ed., xi–xvi, 1918.

[40] Maxwell: Theory of heat, chap. 2; Shaw: Units and unity, *Nature*, 101, 326–328, 1918; A. McAdie: Thermometer scales, *Science* (N. S.), 43, 854, 1916; MONTHLY WEATHER REVIEW, 37, 92, 1909; *Geographical Review*, 4, 214–216, 1917.